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EFFECTS OF EXPOSURE TO CONTINUOUS ROTATION ON NYSTAGMUS PHASE SHIFT

BY

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PENSACOLA, FL~~ORIDA~~ A.

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BUREAU OF MEDICINE AND SURGERY

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SUMMARY PAGE

THE PROBLEM

To evaluate the frequency response characteristics of the horizontal semicircular canals of four naval aviators before and after twelve days of continuous rotations at 10RPM in the Pensacola Slow Rotation Room (SRR), and of one naval aviator exposed to a normal static environment during the same interval.

FINDINGS

Three experimental runs were made before and three additional runs after the SRR exposure period. No consistent differences were noted among subjects.

The ratio $2\,\zeta/\omega_n$, where ζ is the damping ratio and ω_n the undamped natural angular frequency, displayed considerable intra-individual as well as inter-individual variability but was comparable to reported values of the equivalent cupulometric ratio, Π/Δ, reported by other investigators.

Even though the subjects were exposed to prolonged nonphysiological vestibular stimuli, significant changes in the performance characteristics of the horizontal semicircular canals as represented by the $2\,\zeta/\omega_n$ measure were not observed.

INTRODUCTION

Although there exist numerous useful clinical tests of vestibular function, it is also true that the stimulus is not always a quantified one and that the evaluation or estimate of the response is largely dependent upon the clinician's skill and judgment. In view of the potential limitations on manned space vehicle operational efficiency which may be imposed by man's vestibular system in unusual acceleration environments, it is of considerable importance to develop objective measures or indices of the characteristics of the vestibular system which may be systematically related to operational performance.

In previous reports it has been shown how the system transfer function concept and a nystagmus transition technique for measuring the lag of nystagmus slow phase eye velocity behind an angular acceleration stimulus may be used for quantification and identification of semicircular canal performance (7, 12). The present report is an attempt to evaluate the frequency response characteristics of the horizontal semicircular canals of naval aviators before and after another experimental program during which they were to be exposed to a 10 RPM continous rotation for twelve days. Comparison of the performance characteristics (ζ and ω_n, the damping ratio and undamped characteristic angular frequency, respectively) would demonstrate whether the stress of activity in the Pensacola Slow Room (SRR) resulted in alteration of the physiological status of the labyrinths as reflected by these indices.

APPARATUS

STIMULUS

The Human Disorientation Device (HDD) which has been fully described elsewhere (9) was used to generate sinusoidal angular acceleration stimuli. Four frequency-peak acceleration configurations about the vertical axis were derived from the output of a low-frequency function generator (Hewlett-Packard Model 202A) which served as the velocity command signal to the HDD vertical axis drive system. The characteristics of these stimuli and the relevant frequency dependent lag characteristics of the HDD are summarized in Table I.

TABLE I

HDD EXPERIMENTAL STIMULI COMBINATIONS

Cyclic Frequency (cps)	Cyclic Period (sec)	Peak Velocity (deg/sec)	Peak Acceleration (deg/sec²)	HDD Phase Shift (deg)
0.025	40	64	10	0
0.05	20	64	20	2.1
0.10	10	64	40	4.1
0.20	5	64	80	7.0

The ratios of peak acceleration were selected to produce equal magnitudes of peak velocity for each stimulus, thus approximating theoretically equal cupular displacements particularly at the higher frequencies. The magnitude of the peak acceleration at the lowest frequency was chosen so as to avoid extreme departures from linearity of response at any portion of the stimulus frequency spectrum (8). The stimulus sequence in Table I was then used to determine the frequency response of the horizontal semicircular canals before and after exposure to a vestibular stress situation.

The stress situation itself was afforded by an independent study by the authors' colleagues at the Naval School of Aviation Medicine involving twelve days of continuous exposure in the Pensacola Slow Rotation Room (SRR), described previously (6), operating at 10 RPM. During this period, the subjects experienced complex angular and linear acceleration stimuli both in the course of carrying out their assigned tasks and in their normal routine. The results of that study are being reported separately.

RESPONSE

Steady-state ocular nystagmus responses to the HDD test stimuli were recorded by a corneo-retinal potential method. The potentials generated by the horizontal displacements of the eye were derived from silver electrodes at the outer canthi, amplified by a nystagmus signal-conditioner developed for this application, and transmitted over gold slip-ring assemblies to one channel of a direct writing recorder (Sanborn 358) after filtering of muscle-potential artifacts. The nystagmus signal-conditioning unit and electrode techniques have been described in detail in another report (10).

PROCEDURE

EXPERIMENTAL

A group of five healthy males volunteered for the twelve day SRR experiments. All were naval officers, 22 to 24 years of age, in flight training status and had no defects in hearing or equilibrium. Four of them, CHM, RAW, EBS, and CVL, were assigned as experimental subjects to the simulated space station exposure and the fifth man, BBV, who was to serve as a back-up member of the team, was used as a control subject.

Each subject was indoctrinated in the purposes and procedures of the experiment prior to the first test. For each test the subject was secured firmly with his head on the vertical axis; the capsule was completely darkened, but the subject was instructed to keep his eyes open during the four stimulus periods of each run. The duration of the stimulus periods varied as each consisted of a sixty-second interval to eliminate potentially significant transient effects (7, 12) plus an interval sufficient to allow the recording of responses to five complete oscillations.

Three experimental runs were made on each subject before the SRR exposure to obtain baseline data and three runs afterwards to determine whether any change had occurred and, if so, whether there would be recovery to the baseline values. The scheduling of these runs in terms of the number of days preceding or following the continuous rotation interval is summarized in Table II.

TABLE II

HDD EXPERIMENTAL SCHEDULE

TEST DAY RELATIVE TO SRR EXPOSURE						
	Test	CHM	RAW	EBS	CVL	BBV (Control)
	1	-15	-15	-14	-12	-12
Pre-SRR	2	-12	-12	-12	-9	-9
	3	-6	-6	-6	-6	-6
SRR		(12 days of continuous rotation at 10 RPM)				
	1	0	0	0	0	0
Post-SRR	2	3	3	3	3	3
	3	18	18	18	18	18

The control subject, BBV, was assigned to various clerical and other duties in the laboratory during the twelve day SRR run but was not exposed to vestibular stimulation other than that experienced in normal activity.

ANALYTICAL

As described previously (12), the recordings displayed the characteristic sawtooth pattern of ocular nystagmus which alternated in direction with the direction of the sinusoidal acceleration stimulus. The interval between the onset of angular acceleration in one direction and the instant at which the resulting transition in nystagmus direction occurred served as the basic measure of nystagmus phase shift. This interval was compared to the cyclic period of the stimulus and expressed in conventional electrical degree nomenclature where one cycle represents 360 degrees. Since the control signal was used as the reference for determination of onset of acceleration, corrections for the lag characteristics of the HDD were made by subtracting the appropriate HDD shift (see Table I) from the nystagmus phase shift measurements at each test frequency.

RESULTS AND DISCUSSION

Steinhausen's concept (13) of the cupula-endolymph structure of the semicircular canal as a heavily damped torsion pendulum has served as the basis for a theoretical representation in terms of a second-order linear differential equation defining the physical characteristics of the system (5). More recently, by application of system transfer function concepts, this theoretical construct has been quantitatively extended to cover vestibular responses to periodic stimuli and re-expressed in terms of the performance characteristic nomenclature used to describe the functioning of control systems (7). The basic equation of motion, expressed in terms of performance rather than physical characteristics, becomes

$$\ddot{\xi} + 2\,\zeta\,\omega_n\,\dot{\xi} + \omega_n^2\,\xi = \alpha_m \sin \omega t$$

for the case where an externally applied sinusoidal acceleration $\alpha_m \sin \omega t$ is used as the stimulus; ξ is the angular displacement of the endolymph in relation to the skull; and ζ is the damping ratio of the system and ω_n, its undamped characteristic angular frequency.

It has been shown in previous reports how a nystagmic response (obtained, for example, by recording of corneo-retinal potentials) to a sinusoidal angular acceleration stimulus exhibits cyclic transitions in the speed and direction of eye movement corresponding to but lagging the stimulus waveform by some experimentally measurable phase angle ϕ. This angle is defined in terms of the system performance characteristics ζ and ω_n by the following relationship

$$\angle\phi\,(j\,\omega) = -\arctan \frac{2\,\zeta\,\omega/\omega_n}{1 - (\omega/\omega_n)^2}$$

or, if ω, the stimulus frequency, is assumed much less than ω_n,

$$\angle\,\phi\,(j\,\omega) \cong -\arctan 2\,\zeta\,\omega/\omega_n.$$

It is then possible simply by measuring the phase shift angle ϕ at a single low frequency, e.g., 0.025 cps in the present study, to determine the value of the parametric ratio $2\,\zeta/\omega_n$ by

$$2\,\zeta/\omega_n \cong (\tan\phi)/2\pi\,F = 6.37\,\tan\phi, \text{ where } F = 0.025 \text{ cps}$$

This index will reflect any over-all changes in the physiological status of the labyrinth due to changes in viscous damping or cupula stiffness or both. It corresponds to the ratio Π/Δ measured by standard cupulometric techniques (4) which utilize non-periodic impulse type stimuli.

Measurement of the phase angle at additional frequencies higher than 0.025 cps offers distinct advantages in that a plot of phase angle against frequency will demonstrate the actual trend of the obtained data and, if appropriate frequencies have been utilized, graphic interpolation will give a direct measure of the stimulus frequency at which $\phi = 90°$, i.e., of ω_n. For these reasons, the mean phase data were also measured at 0.05, 0.10, and 0.20 cps.

The phase shift at each of four stimulus frequencies for left and right accelerations was determined for each subject based on the measurement of five cycles in either direction. These values together with their standard deviations are summarized in Tables III-VII. Examination of the over-all data revealed no consistent or significant differences attributable to the direction of acceleration, and the combined means are presented in Figure 1 by subject and experiment. The frequency dependence of nystagmus phase shift measurements, as previously shown, is reaffirmed.

It is evident from the data in Figure 1 that it was not possible to determine by graphic interpolation the value of ω_n for the cupula-endolymph system; apparatus limitations on the upper end of the available stimulus frequency spectrum prevented our obtaining a direct estimate of ω_n values for these subjects. Since ω_n is obviously greater than the lowest stimulus frequency, an estimate of the ratio of system damping to system stiffness can be obtained. This ratio, $2\zeta/\omega_n$, can then be used as a system performance index to evaluate whether the interpolated stress of twelve days' continuous residence in a slowly rotating environment and the associated exposure to complex acceleration stresses will alter ζ, ω_n, or both and hence, presumably, the physiological status of the labyrinth.

The ratio $2\zeta/\omega_n$ must be considered as constant or time-variant in a linear system of second-order. Any mechanism of this type, such as the cupula-endolymph system, may be subjected to levels of input excitation which may result in overloading and operation in a nonlinear mode. Such overloading has been demonstrated in a previous study by the present authors (8). Van Egmond (3) also has shown that a rotation test of vestibular function, such as the Barany, using very high-level impulse accelerations as stimuli can result in a depression of the damping/stiffness ratio, Π/Δ, as measured by the sensation cupulogram after only one test. Aschan (1) has shown, moreover, that military aviators actively engaged in aerobatics and similar stressful maneuvers demonstrate lower values of Π/Δ than do nonaviators.

The trends in $2\zeta/\omega_n$ values over the three pre-SRR and three post-SRR experimental sessions are presented graphically in Figure 2 for each subject. (Because the phase shift angles were much less than 90 degrees and their variability small, $2\zeta/\omega_n$ was calculated from the tangent of the mean angle, rather than the mean tangent of the angles, as a convenient approximation.) In all subjects except CVL there was no significant difference between left and right directed accelerations at the

TABLE III

Mean Phase Shift (ϕ)* and Standard Deviation (s) as a Function of Frequency by Direction of Stimulus Acceleration During Three Experiments Before and After Twelve Continuous Days' Exposure to 10 RPM Rotating Environment for Subject CHM

Test Period	Experiment	Stimulus Direction	0.025		0.05		0.10		0.20	
			ϕ	s	ϕ	s	ϕ	s	ϕ	s
Pre-SRR	1	Left	62.8	2.99	77.1	1.69	82.3	3.72	91.6	1.25
		Right	66.0	1.22	76.8	1.07	87.6	3.73	86.0	3.70
	2	Left	66.7	2.22	74.4	2.42	90.3	1.03	95.3	5.14
		Right	70.2	2.50	70.3	2.58	77.2	1.80	89.0	6.30
	3	Left	65.2	1.52	74.8	1.93	82.7	2.14	93.0	2.05
		Right	64.4	0.81	75.7	1.29	81.9	1.21	89.6	2.38
Post SRR	1	Left	54.3	5.01	72.9	0.86	79.3	1.56	89.6	2.63
		Right	64.2	0.71	72.3	1.15	78.4	1.10	86.7	1.30
	2	Left	60.8	0.51	72.2	1.35	78.4	1.60	87.3	2.02
		Right	60.9	0.93	71.5	0.86	77.8	1.30	88.4	1.53
	3	Left	59.4	1.61	72.5	1.17	90.2	3.88	99.3	2.39
		Right	59.2	0.84	71.4	0.59	85.8	3.73	95.9	2.02

Stimulus Frequency (cps) spans the columns 0.025, 0.05, 0.10, 0.20.

*Each datum represents the mean phase shift in electrical degrees based on five cycles recorded after a 60 second preliminary oscillation.

TABLE IV

Mean Phase Shift (ϕ)* and Standard Deviation (s) as a Function of Frequency by Direction of Stimulus Acceleration During Three Experiments Before and After Twelve Continuous Days' Exposure to 10 RPM Rotating Environment for Subject RAW

Test Period	Experiment	Stimulus Direction	0.025 ϕ	0.025 s	0.05 ϕ	0.05 s	0.10 ϕ	0.10 s	0.20 ϕ	0.20 s
Pre-SRR	1	Left	70.2	1.75	76.5	1.35	85.0	1.64	84.4	2 02
		Right	71.1	1.43	76.8	2.25	82.7	2.73	84.4	2.02
	2	Left	71.7	2.59	74.9	1.21	74.9	5.58	87.3	4.51
		Right	74.9	2.05	75.0	1.47	75.4	3.32	89.5	1.25
	3	Left	70.3	1.53	73.9	0.80	73.7	1.22	85.0	4.66
		Right	70.9	0.97	74.4	1.60	75.7	1.88	86.7	3.70
Post SRR	1	Left	66.4	0.89	73.3	1.76	74.9	2.21	86.1	1.59
		Right	69.6	0.76	73.7	0.01	75.2	2.21	88.4	2.54
	2	Left	67.5	1.55	71.5	1.60	74.6	2.16	85.0	3.12
		Right	68.9	2.31	71.5	1.53	75.8	2.73	85.0	2.39
	3	Left	70.7	1.11	73.2	1.68	77.0	1.81	86.1	1.59
		Right	70.3	0.79	72.6	0.80	76.9	1.80	86.1	1.59

Stimulus Frequency (cps)

*Each datum represents the mean phase shift in electrical degrees based on five cycles recorded after a 60 second preliminary oscillation.

TABLE V

Mean Phase Shift (ϕ)* and Standard Deviation (s) as a Function of Frequency by Direction of Stimulus Acceleration During Three Experiments Before and After Twelve Continuous Days' Exposure to 10 RPM Rotating Environment for Subject EBS

Test Period	Experiment	Stimulus Direction	0.025		0.05		0.10		0.20	
			ϕ	s	ϕ	s	ϕ	s	ϕ	s
	1	Left	71.2	2.04	75.7	2.71	76.9	1.87	85.6	1.59
		Right	69.5	2.76	75.8	1.94	79.3	4.41	79.3	3.12
Pre-	2	Left	72.0	2.10	75.3	1.11	73.2	2.38	83.8	5.84
SRR		Right	71.1	2.44	74.9	2.40	74.9	3.65	81.6	2.02
	3	Left	66.6	0.99	74.9	0.96	82.7	1.21	87.8	2.38
		Right	65.1	0.41	74.5	0.96	82.2	2.64	88.4	2.54
	1	Left	60.8	1.72	73.7	0.59	78.7	1.03	87.3	2.02
		Right	63.5	1.82	72.8	2.89	77.5	1.22	86.1	1.59
Post	2	Left	64.3	0.72	73.5	0.59	76.4	1.66	87.3	2.02
SRR		Right	64.3	1.72	73.5	0.59	76.1	1.21	87.3	2.85
	3	Left	66.2	0.73	73.0	0.94	74.9	1.29	82.6	1.53
		Right	66.7	0.25	72.4	0.80	75.4	1.03	84.3	2.39

Stimulus Frequency (cps)

*Each datum represents the mean phase shift in electrical degrees based on five cycles recorded after a 60 second preliminary oscillation.

TABLE VI

Mean Phase Shift (ϕ)* and Standard Deviation (s) as a Function of Frequency by Direction of Stimulus Acceleration During Three Experiments Before and After Twelve Continuous Days' Exposure to 10 RPM Rotating Environment for Subject CVL

Test Period	Experiment	Stimulus Direction	0.025		0.05		0.10		0.20	
			ϕ	s	ϕ	s	ϕ	s	ϕ	s
Pre-SRR	1	Left	74.4	2.78	75.3	1.31	82.5	1.96	86.1	3.24
		Right	65.9	0.92	72.2	2.50	78.1	1.64	85.6	1.59
	2	Left	72.7	0.96	75.1	1.35	84.5	1.45	87.8	2.38
		Right	63.2	2.40	75.3	0.81	82.1	1.96	88.4	3.26
	3	Left	70.2	1.05	75.7	1.29	85.6	1.90	86.1	1.59
		Right	60.3	0.55	74.3	1.92	83.6	1.64	85.6	2.55
Post SRR	1	Left	65.0	1.28	70.9	0.82	75.8	1.45	83.3	4.34
		Right	59.1	0.84	71.8	1.17	73.5	3.02	81.6	2.85
	2	Left	67.0	2.09	73.3	0.80	74.9	2.18	84.4	2.02
		Right	60.7	3.58	73.3	1.53	75.5	1.88	83.9	2.38
	3	Left	65.6	0.76	73.3	0.80	78.6	1.22	85.4	1.59
		Right	64.3	0.67	72.3	0.91	76.9	1.02	84.9	2.55

Stimulus Frequency (cps) spans the columns 0.025, 0.05, 0.10, 0.20.

*Each datum represents the mean phase shift in electrical degrees based on five cycles recorded after a 60 second preliminary oscillation.

TABLE VII

Mean Phase Shift (ϕ)* and Standard Deviation (s) as a Function of Frequency by Direction of Stimulus Acceleration During Three Experiments Before and After Twelve Continuous Days' Exposure to 10 RPM Rotating Environment for Control Subject BBV

Test Period	Experiment	Stimulus Direction	0.025 ϕ	0.025 s	0.05 ϕ	0.05 s	0.10 ϕ	0.10 s	0.20 ϕ	0.20 s
Pre-SRR	1	Left	72.3	1.65	75.4	1.22	85.9	3.10	88.4	2.54
		Right	69.0	1.25	76.4	1.41	84.2	3.18	88.4	3.26
	2	Left	66.1	0.69	72.3	1.89	78.4	1.88	85.6	3.24
		Right	66.4	0.83	71.7	2.09	75.2	0.82	86.1	4.33
	3	Left	63.8	0.54	74.3	1.40	80.4	1.22	89.6	3.73
		Right	64.4	1.28	74.3	1.31	77.8	2.84	87.9	3.14
Post SRR	1	Left	60.2	2.64	72.6	2.54	75.7	3.12	86.7	2.39
		Right	58.7	1.25	73.0	1.67	78.0	2.60	88.4	4.77
	2	Left	66.5	0.48	74.0	0.63	78.7	1.45	83.9	2.38
		Right	65.7	0.67	74.4	0.59	77.2	1.45	85.0	2.39
	3	Left	65.6	0.91	73.2	1.56	77.7	1.66	82.7	1.53
		Right	65.1	0.58	73.0	1.57	74.9	1.29	83.3	1.53

Stimulus Frequency (cps)

*Each datum represents the mean phase shift in electrical degrees based on five cycles recorded after a 60 second preliminary oscillation.

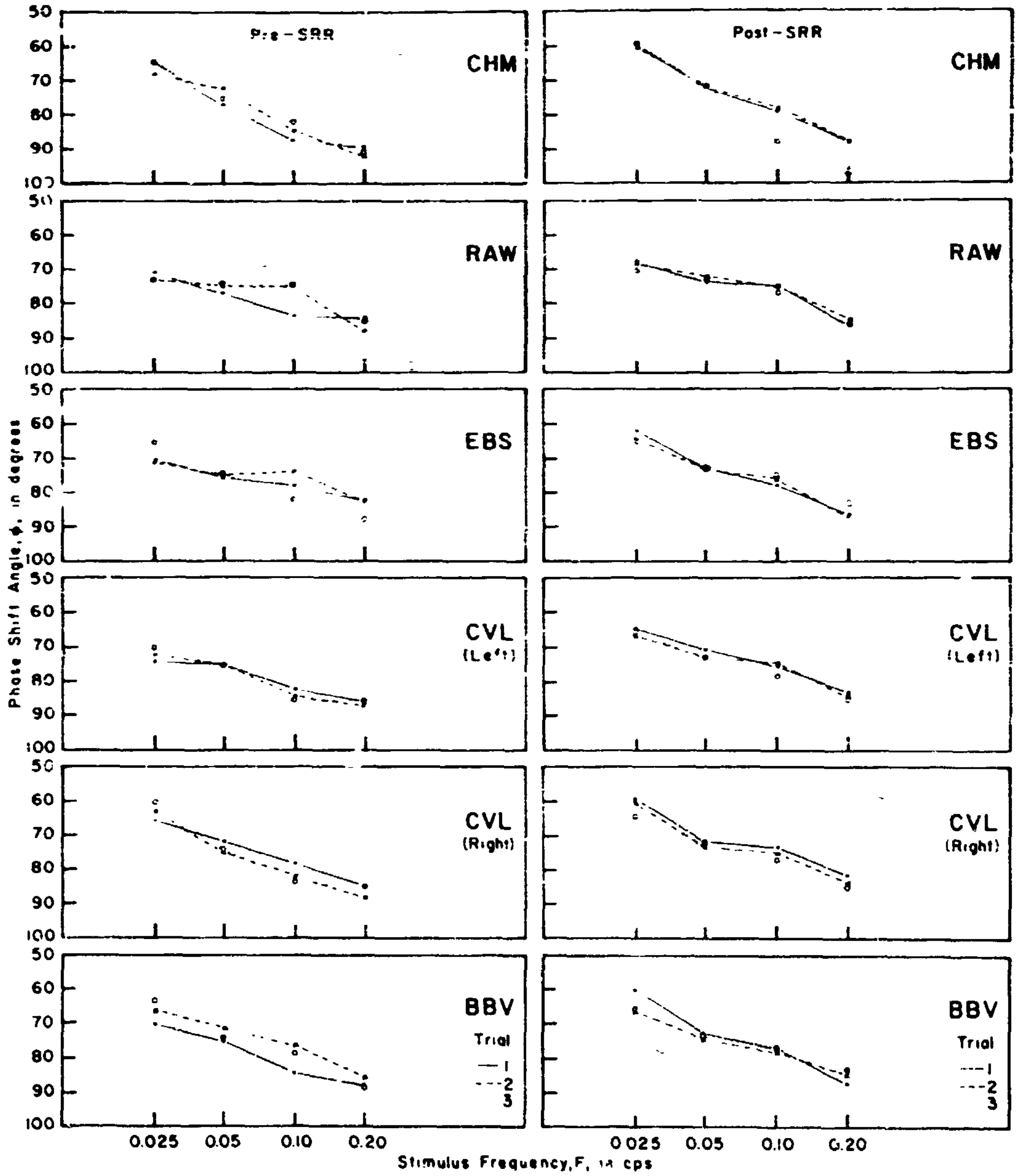

FIGURE 1

Nystagmus Phase Shift Data Plotted Against Cyclic Frequency of Sinusoidal Angular Acceleration Stimulus (See Text). Response to Left and Right Accelerations Combined for All Subjects Other Than CVL for Each of Three Trials Presented Before and After the SRR Exposure.

0.025 cps frequency selected for determining tan ϕ, and the data were combined. CVL, however, showed distinctly different responses at this frequency to left and right accelerations, and the $2\zeta/\omega_n$ values are shown separately.

The $2\zeta/\omega_n$ values are also tabulated in Table VIII together with the mean standard deviation, standard error, and fiducial limits at the 5 per cent level. As can be seen from Figure 2, there seems to be a general tendency for the post-SRR means to be depressed relative to the pre-SRR means. Whether this is significant or not may be evaluated from the data of Table VIII in which the $2\zeta/\omega_n$ values are tabulated together with the means (x), standard deviation(s), standard errors (s_x), and fiducial limits

TABLE VIII

Summary of $2\zeta/\omega_n$ Values and Means and Fiducial Limits Based on the Three Pre-SRR Experiments

		SUBJECT					
Expericent		CHM	RAW	EBS	CVL(L)	CVL(R)	BBV
	1	13.3	18.2	17.8	22.8	14.2	18.2
Pre-SRR	2	16.2	21.2	19.0	20.5	12.6	14.5
	3	13.5	18.1	14.2	17.7	11.2	12.8
x		14.3	19.2	17.0	20.3	12.7	15.2
s		1.6	1.8	2.5	3.6	2.1	2.8
s_x		0.9	1.0	1.5	2.1	1.2	1.6
$t_{.05}\, s_x$		3.9	4.3	6.4	9.0	5.2	6.9
$x + t_{.05}\, s_x$		18.2	23.5	23.4	29.3	17.9	22.1
$x - t_{.05}\, s_x$		10.4	14.9	10.6	11.3	7.5	8.3
	1	10.7	15.8	12.1	13.7	10.6	10.8
Post-SRR	2	11.4	15.9	13.2	15.0	11.4	14.4
	3	10.7	18.0	14.7	14.0	13.2	13.9

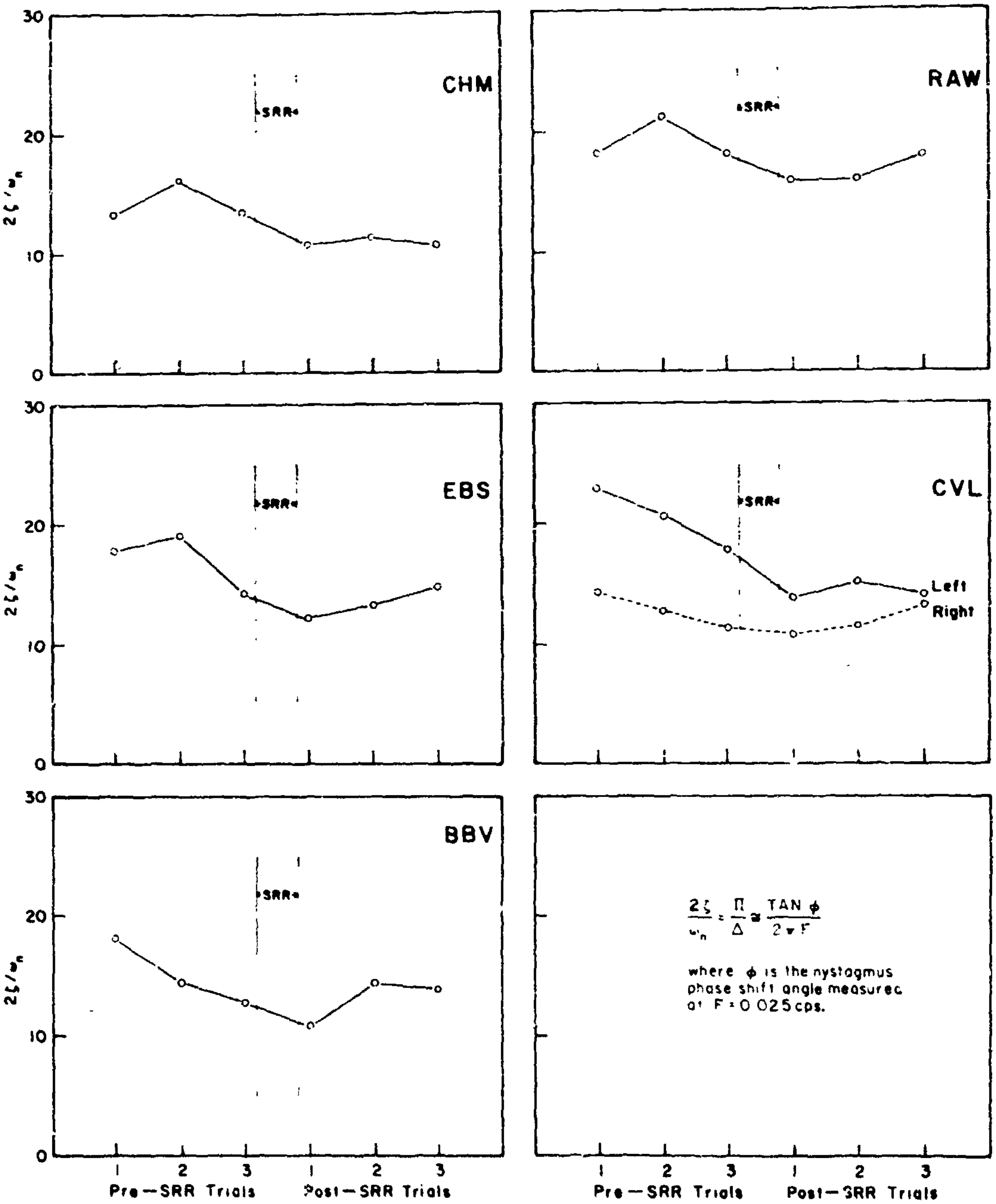

FIGURE 2

Calculated Values of Cupula-Endolymph Damping Stiffness Ratio, $2\ \zeta/\omega_n$, Plotted Against Experimental Trials. Responses to Left and Right Accelerations Combined for All Subjects Other Than CVL.

at the 5 per cent level ($x \pm t_{.05} s_x$) for the pre-SRR data for each subject. It may readily be seen that in all instances the post-SRR values fall within the 0.95 fiducial interval and hence can be considered to fall within the normal limits of $2\zeta/\omega_n$ as determined before the twelve day exposure to continuous rotation at 10 RPM.

The average value of 14.8 for $2\zeta/\omega_n$ based on all the data is also consistent with average values of 16 seconds (4), 11 seconds with a range of 6 to 24 seconds derived from average data on 320 normals reported by Aschan et al (2) for the equivalent ratio II/Δ obtained from the normal nystagmus cupulogram.

The present results taken in conjunction with the findings of other investigators have interesting implications. It has been shown by us that experimental overloading of the oculovestibular system can produce changes in the magnitude of the stimulus-response phase shift and hence in the time characteristics of the system. These changes have been related to the idealized cupula transfer function portion of the overall system transfer function since it was assumed in the basic theoretical formulation that the idealized nystagmus transfer function is frequency-invariant, i.e., the eye velocity response is essentially in phase with the cupular stimulus. Since significant changes in phase shift or derived measures are not demonstrable in the current study, presumably even the prolonged vestibular stimulation represented by residence in a continuously rotating environment of this type is not sufficiently severe or "nonphysiological" to affect the physical performance characteristics of the end-organ itself. This finding cannot, however, be taken to imply that no effects can be shown on oculovestibular system function as a whole. Measurement of the magnitude of slow-phase eye velocities could be expected to show changes in amplitude which could be related to the effects of habituation or adaptation. That such effects do occur has been amply demonstrated by others, and hence the present study can be taken to indicate that they originate beyond the end-organ in the central nervous pathways or the oculomotor system.

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